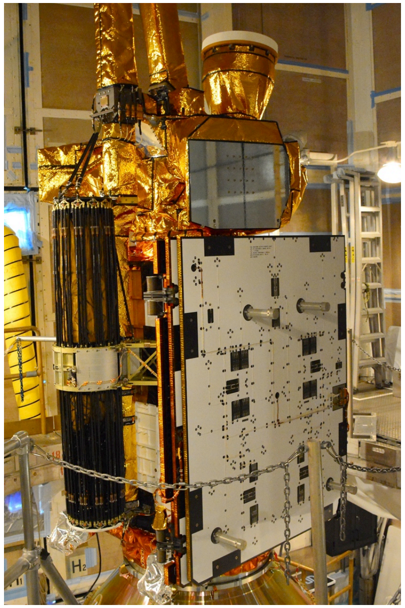
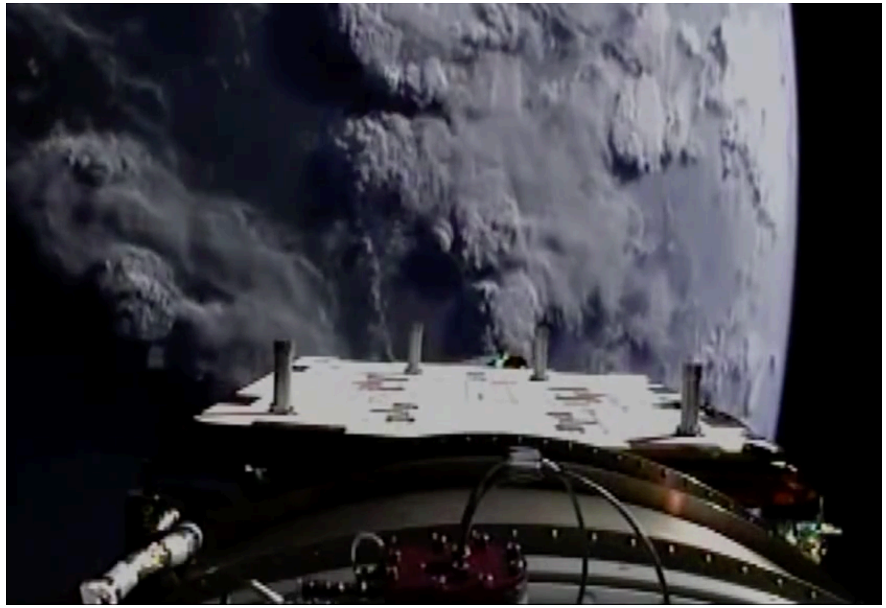
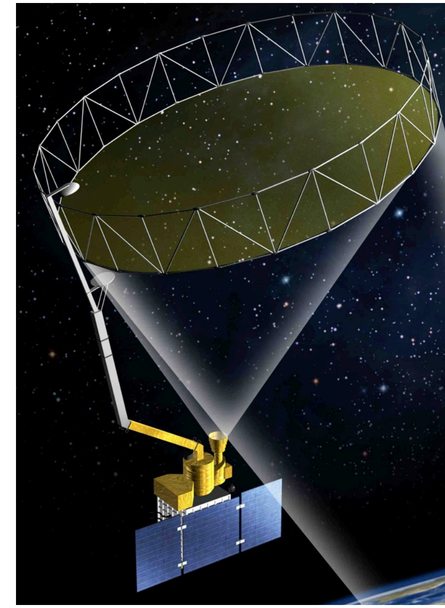






In-Flight Pointing Accuracy Assessment and GNC Commissioning Overview for the Dual-Spinning SMAP (Soil Moisture Active Passive) Spacecraft

Todd Brown & Tina Sung

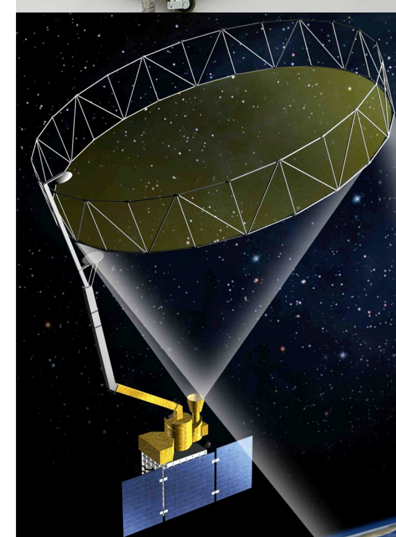
SMAP GNC Ops Team

Jet Propulsion Laboratory, California Institute of Technology

February 2017

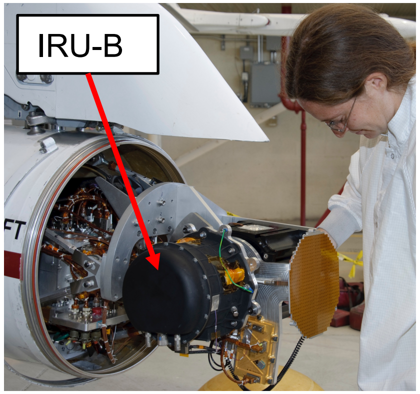
SMAP Mission and Spacecraft Overview

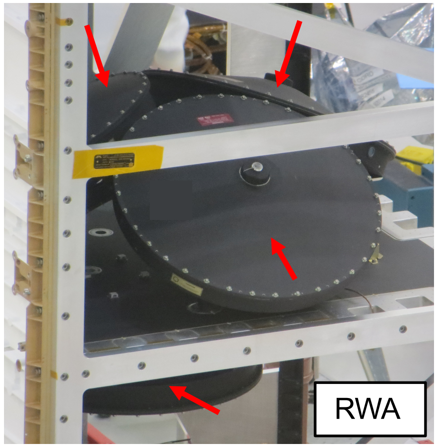
- Mission: Measure global soil moisture levels in top 2 inches of soil every 2-3 days, as well as detect freeze/thaw boundary
- Date Launched: Jan 31, 2015
- Prime Mission Length: 3 years
- 2 Science Instruments:
  1. L-Band 1.41 GHz Radiometer provided by Goddard SFC
  2. L-Band 1.22-1.3 GHz Radar provided by JPL
     - Radar in-flight anomaly on July 7, 2015. Instrument no longer functions
- Launch Vehicle: ULA Delta II (Vandenberg Air Force Base)
- Orbit Altitude: ~690 km polar sun synchronous orbit
- 6:00 local mean solar time
  - Continuous sunlight except for <20 minute eclipses in summer season
- Spacecraft Overview
  - Conical-scanning, dual-spinning, 3-axis stabilized
  - Spin rate of Spun Platform Assembly (SPA): 14.6 rpm
  - 6 meter mesh reflector and 5 meter boom on SPA
  - 944 kg
  - Spacecraft designed and assembled at JPL

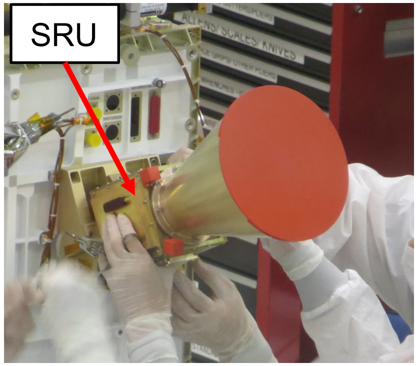


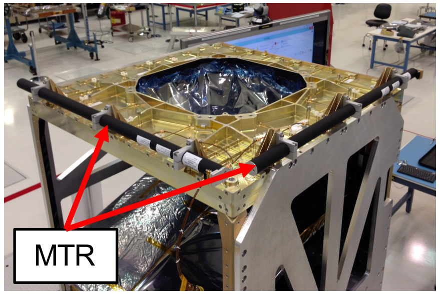
SMAP GNC Overview

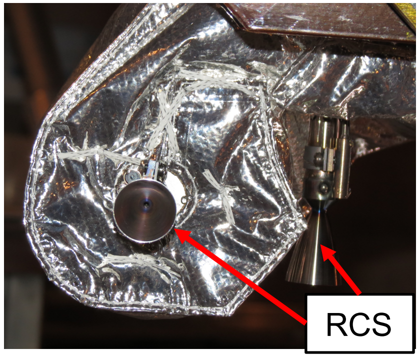
- **GNC Hardware**
  - Eight 4.5 N RCS Thrusters
  - Four 250 Nms RWAs
  - 2 analog Coarse Sun Sensor (CSS) pyramids (8 heads total)
  - 1 Stellar Reference Unit (SRU)
  - 2 inertial reference units. IRU-A prime / IRU-B unpowered backup
    - "IRUs" are actually IMUs (include accelerometers)
  - One 3-Axis Magnetometer (TAM)
  - 3 Magnetic Torque Rods (MTRs)
  - In-house Torque Drive Electronics (TDEs)
  - No GPS. Doppler orbit determination & uplinked ephemeris
- **GNC Controller Description**
  - RCS Control Mode
    - Post launch, for maneuvers, and some extreme fault cases
  - RWA Control Mode
    - Science mode, safe mode, spin-up mode
  - Idle Control Mode (GNC control inactive)
    - Deployment of solar arrays, boom, reflector, and pyro firings
  - Momentum Control Loop
    - SMAP maintains a zero-momentum state
    - Momentum estimated on-board and then TAM data used autonomously to send commands to MTRs to unload momentum

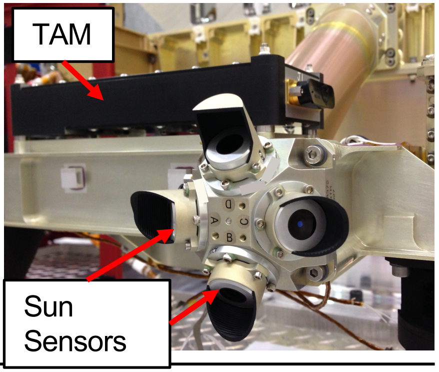










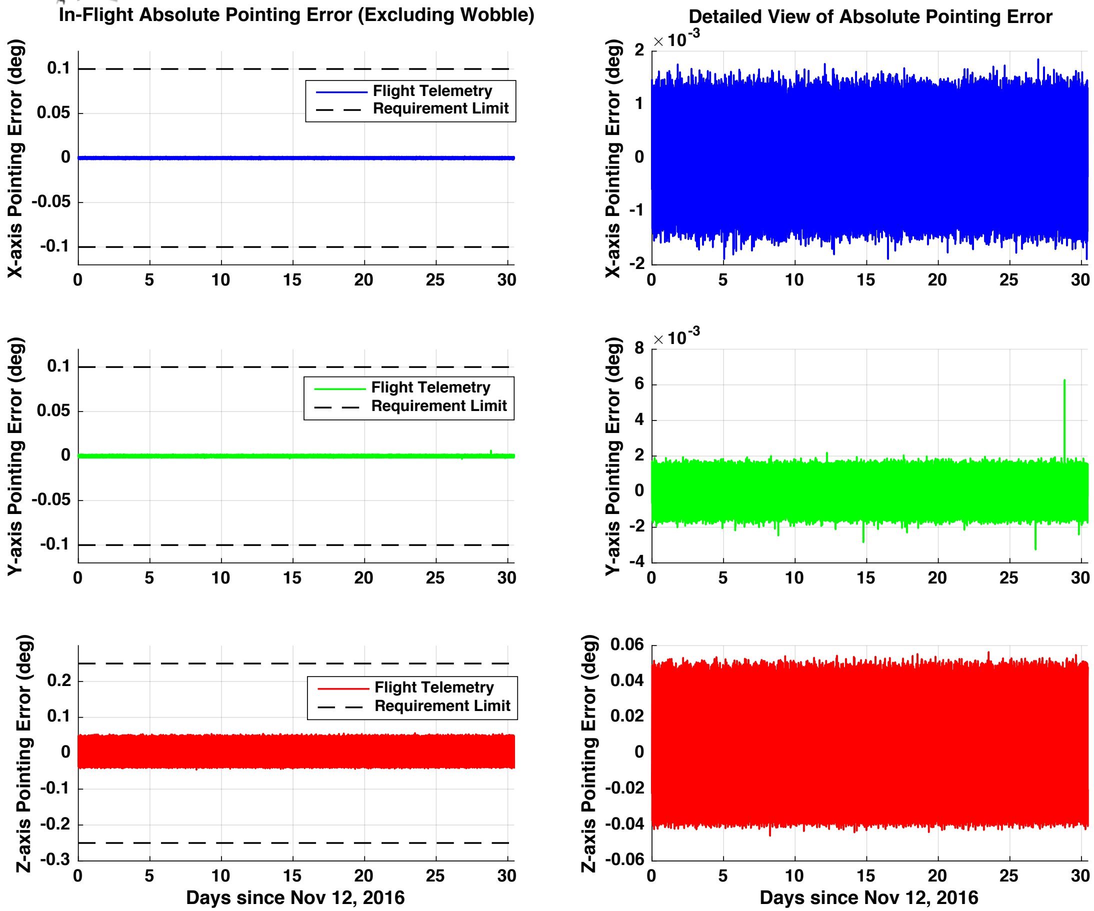


SMAP GNC Pointing Accuracy Requirements

GNC Pointing Requirements	GNC Requirement Summary	Unit	Requirement	Pre-Launch Expectation
GNC Absolute Pointing Error (X & Y Axes)	Over a one-month period of science ops, GNC must maintain the absolute pointing error angle about the SC X & Y axes (excluding wobble) to within 0.1 deg (3σ)	deg	0.1	0.06
GNC Absolute Pointing Error (Z-Axis)	Over a one-month period of science ops, GNC must maintain the absolute pointing error angle about the SC Z axis (excluding wobble) to within 0.28 deg (3σ)	deg	0.28	0.12
GNC Angular Rate Error	Over a one-month period of science ops, GNC must maintain the angular rate of the spacecraft (excluding wobble) to less than 0.070 deg/s (3σ)	deg/sec	0.07	0.04
GNC Attitude Knowledge Error	Over a one-month period of science ops, GNC must ensure that the estimated attitude knowledge error is less than 0.04 deg (3σ)	deg	0.04	0.02

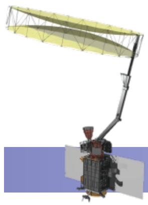
- **Requirement Overview**
  - GNC requirements place limits on:
    - Absolute pointing accuracy
    - Angular rate error
    - Attitude knowledge relative to inertial (J2000) frame
  - Looser pointing requirement on Z-axis
    - Z-axis is axis of rotation, so error around Z only effects the timing of the science data
    - Z-axis has Minimum Moment of Inertia
    - Z-axis experiences large disturbance torques from BAPTA (spin-motor)

SMAP GNC Absolute Pointing Error

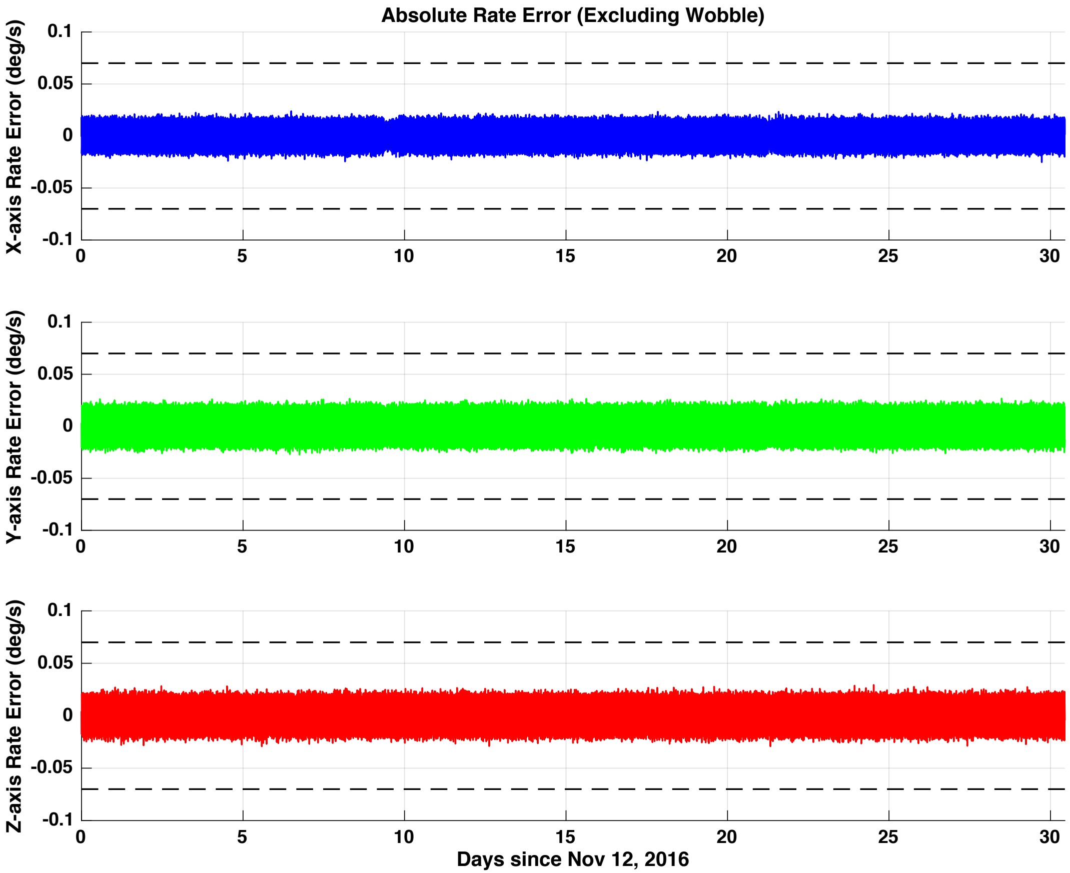


GNC Pointing Requirements	GNC Requirement Summary	Unit	Requirement	Pre-Launch Expectation	Flight Telemetry
GNC Absolute Pointing Error (X & Y Axes)	Over a one-month period of science ops, GNC must maintain the absolute pointing error angle about the SC X & Y axes (excluding wobble) to within 0.1 deg (3σ)	deg	0.1	0.06	**0.002**
GNC Absolute Pointing Error (Z-Axis)	Over a one-month period of science ops, GNC must maintain the absolute pointing error angle about the SC Z axis (excluding wobble) to within 0.28 deg (3σ)	deg	0.28	0.12	**0.066**

- SMAP GNC In-Flight Pointing Accuracy Telemetry
  - Plot includes flight telemetry from Nov 12 through Dec 12, 2016
    - 31 days of uninterrupted nadir pointed science
  - Spike in Y-axis error due to interruption in ground correlation of SCLK (spacecraft clock) to ephemeris time.
    - Ground issue resulted in minor ephemeris error (~6 milli-deg)
    - Spike is example of ~7σ outlier from a non-Gaussian error source
- GNC Subsystem easily meets the Absolute Pointing Accuracy requirements for X, Y, and Z axes, with significant margin
  - Also outperforms conservative prelaunch performance estimates

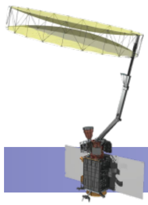


SMAP GNC Rate Error

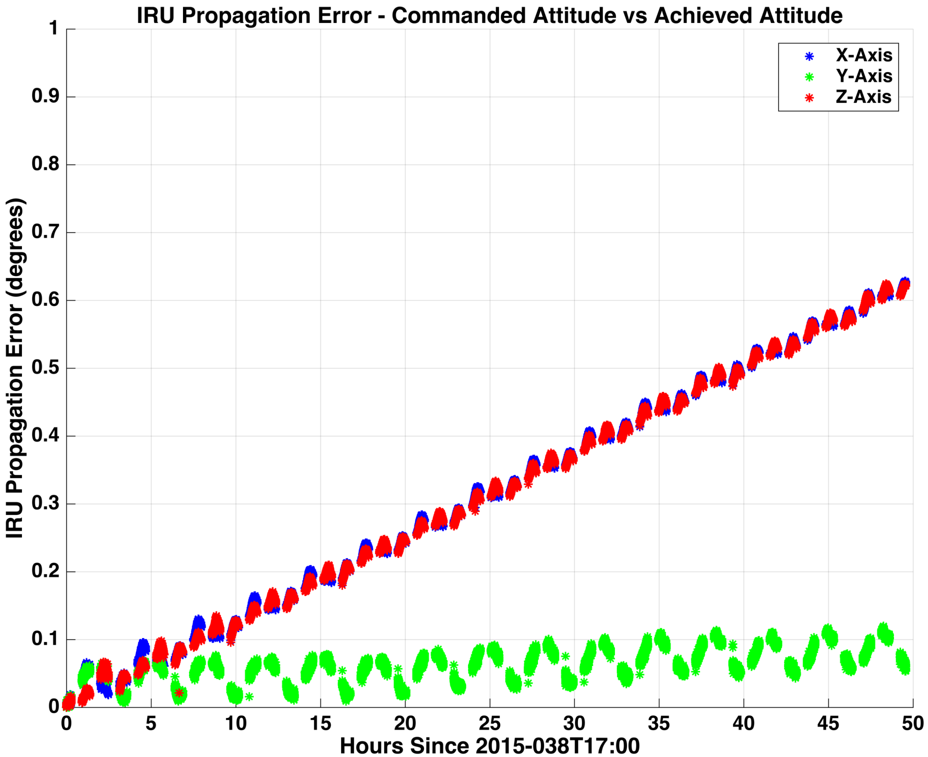


- SMAP GNC In-Flight Rate Control Telemetry
  - Plot includes flight telemetry from Nov 12 through Dec 12, 2016
    - 31 days of uninterrupted nadir pointed science
- GNC controls inertial body rate (relative to nadir tracking target attitude) to within 22 milli-deg/sec (3σ)
- GNC Angular Rate Error requirement met with significant margin for all axes
  - Also outperforms conservative prelaunch performance estimates

GNC Pointing Requirements	GNC Requirement Summary	Unit	Requirement	Pre-Launch Expectation	Flight Telemetry
GNC Angular Rate Error	Over a one-month period of science ops, GNC must maintain the angular rate of the spacecraft (excluding wobble) to less than 0.070 deg/s (3σ)	deg/sec	0.07	0.04	**0.022**



SMAP GNC Attitude Knowledge Error



Date	Duration of Attitude Propagation Using Only IRU Data (Hours)	Per-Axis IRU Attitude Propagation Uncertainty (deg/day)**		
		X-Axis	Y-Axis	Z-Axis
2/6/2015	49.6	0.30	0.03	0.30
2/19/2015	18.7	0.29	0.03	0.29
5/12/2015	24.9	0.24	-0.05	0.22
6/16/2015	22.4	0.18	0.01	0.20
9/5/2016	1.6	0.23	0.01	0.12
9/27/2016	2.3	0.14	0.45	0.22

- In-flight attitude knowledge error dependent upon:
  - IRU-only attitude propagation error: ~0.3 deg/day
  - Duration of SRU data outages
    - Moon occultations of <5.5 min occur at science attitude
- IRU performance determined from S/C operations during safe mode, when SRU is on, but not in control loop
- GNC performance easily meets the attitude knowledge requirement

GNC Pointing Requirements	GNC Requirement Summary	Unit	Requirement	Pre-Launch Expectation	Flight Telemetry
GNC Attitude Knowledge Error	Over a one-month period of science ops, GNC must ensure that the estimated attitude knowledge error is less than 0.04 deg (3σ)	deg	0.04	0.02	**0.001**

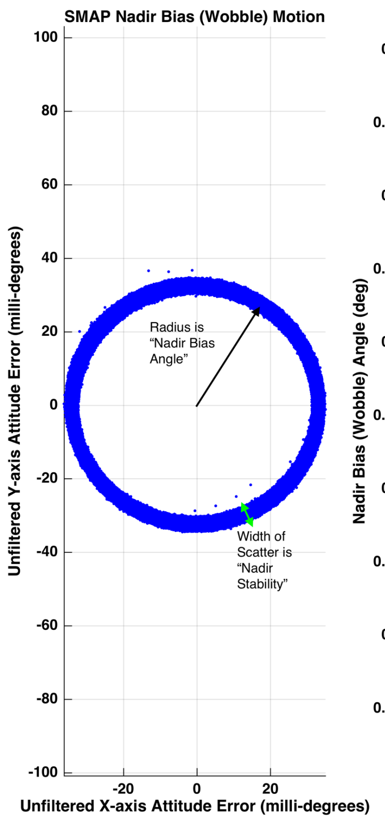
SMAP GNC Pointing Accuracy Requirements

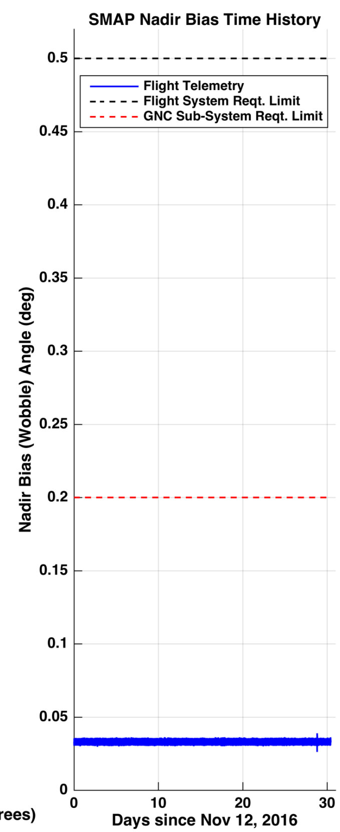
GNC Pointing Requirements	GNC Requirement Summary	Unit	Requirement	Pre-Launch Expectation	Flight Telemetry	Achieved Margin	Comply?
GNC Absolute Pointing Error (X & Y Axes)	Over a one-month period of science ops, GNC must maintain the absolute pointing error angle about the SC X & Y axes (excluding wobble) to within 0.1 deg (3σ)	deg	0.1	0.06	**0.002**	**98%**	Yes
GNC Absolute Pointing Error (Z-Axis)	Over a one-month period of science ops, GNC must maintain the absolute pointing error angle about the SC Z axis (excluding wobble) to within 0.28 deg (3σ)	deg	0.28	0.12	**0.066**	**76%**	Yes
GNC Angular Rate Error	Over a one-month period of science ops, GNC must maintain the angular rate of the spacecraft (excluding wobble) to less than 0.070 deg/s (3σ)	deg/sec	0.07	0.04	**0.022**	**69%**	Yes
GNC Attitude Knowledge Error	Over a one-month period of science ops, GNC must ensure that the estimated attitude knowledge error is less than 0.04 deg (3σ)	deg	0.04	0.02	**0.001**	**97%**	Yes

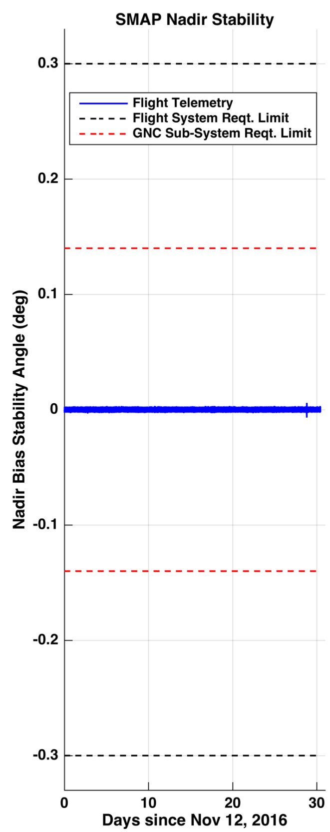
- **GNC Meets All Pointing Accuracy Requirements With Significant Margin**
  – 69-98% margin for all 4 GNC requirements
  – GNC out-performed conservative pre-launch estimates based on detailed kinematic and dynamical modeling
  – "3σ over one month" requirement structure was a wise choice, because it excludes non-Gaussian interruptions/disturbances that are beyond the controller design

Flight System Nadir Pointing Accuracy

Flight System Pointing Requirements	Flight System Requirement Summary	Unit	Requirement (Spacecraft + Instrument)	Spacecraft Allocation	Pre-Launch Expectation	Flight Telemetry	Margin Relative to Spacecraft Allocation	Comply?
System Nadir Bias Angle	Over a one-month period of science ops, the observatory mean boresight nadir angle (including wobble) must be biased no more than 0.5 deg (3σ) from the commanded nadir pointing direction	deg	0.5	0.2	0.072	**0.033***	**84%**	Yes
System Nadir Stability	Over a one-month period of science ops, the instantaneous observatory boresight nadir angle (including wobble) must remain within 0.3 deg (3σ) of the mean antenna boresight nadir angle	deg	0.3	0.14	0.073	**0.003***	**98%**	Yes
System Nadir Knowledge	During Science observations, the antenna boresight nadir angle must be **known** to within 0.1 deg (3σ) of instantaneous antenna boresight nadir angle	deg	0.1	0.07	0.045	**0.004***	**94%**	Yes



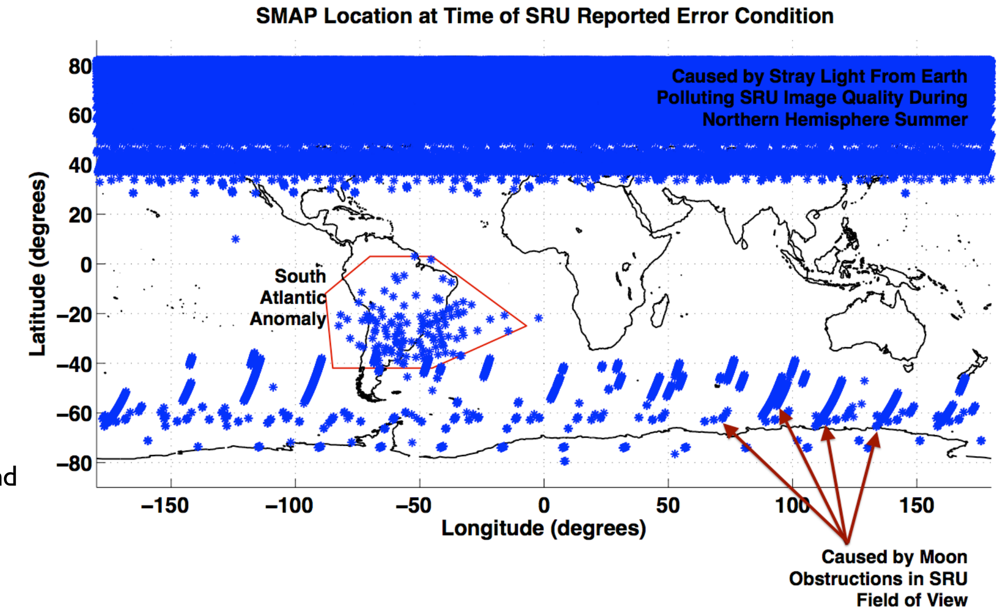




- **System Pointing Performance**
  - Separate from GNC performance
  - Flight System includes allocations for the Science Instruments and Spacecraft
    - "Spacecraft" includes GNC among others
  - **Flight System "Nadir Pointing" requirements *appear* to be met with substantial margin**
  - Caveat: Performance here based on GNC telemetry, and does not include unobservable error sources, including:
    - Electro-mechanical boresight bias
    - Thermomechanical variations in SC structure
    - RF scattering
    - Antenna flex/distortion due to centripetal acceleration

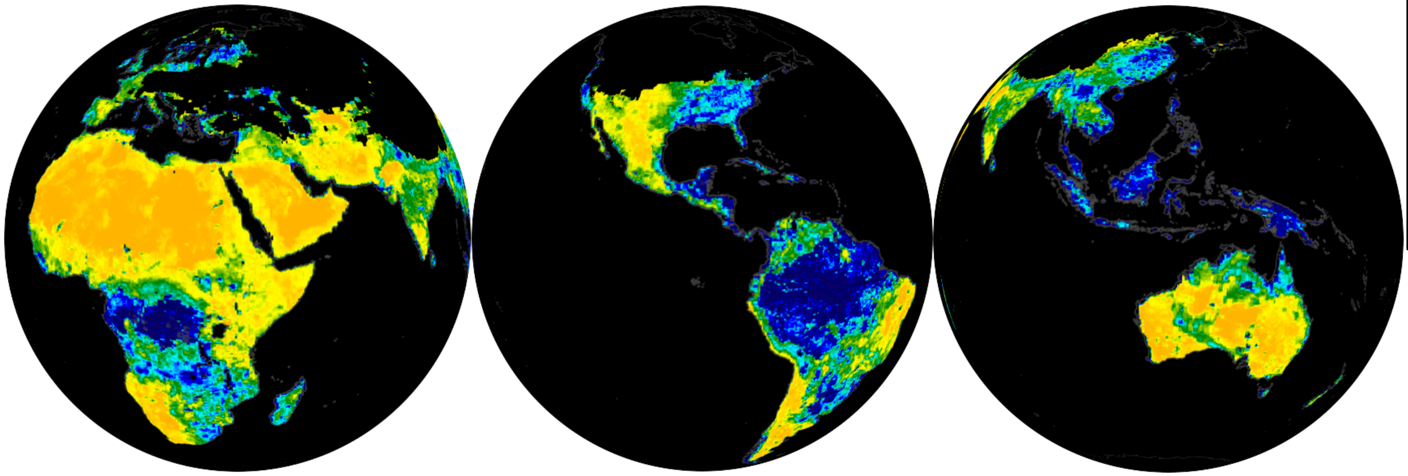
SMAP SRU Flight Experience

- SMAP SRU has been the most troublesome piece of GNC hardware
- SMAP SRU has exhibited three independent unexpected behaviors
- SRU Issue #1
  - SRU autonomously reports "excessive number of stars" error condition in its telemetry
  - Condition presented itself >500,000 times in flight
    - Frequency could mask visibility of other errors
  - Error condition triggered by: **(a)** stray light from Earth albedo reflecting off inside of baffles, **(b)** moon in the SRU field of view, and **(c)** elevated radiation environment of the South Atlantic Anomaly
  - SRU continues to produce attitude estimates even in the presence of the error condition
- SRU Issue #2
  - SRU has experienced 5 in-flight unplanned resets
  - Assumed to be due to SEU (sudden event upset) from high energy charged particle
  - SMAP flight software response to resets: safe the vehicle
    - This was changed in later flight software update
  - SRU resets resulted in 3 safing events and nearly a 4th
- SRU Issue #3
  - Some Earth obstructions caused SRU to cease producing attitude estimates
  - Error condition can only be resolved by resetting the hardware
  - No hardware fix currently available
  - Operational work around: command the SRU to STANDBY before any Earth obstruction



In-flight SRU Checkout:
- SRU attitude estimate compared to TAM/CSS derived attitude estimate with ground tool
- SRU photos downlinked to confirm no optical contamination

Summary & Conclusions

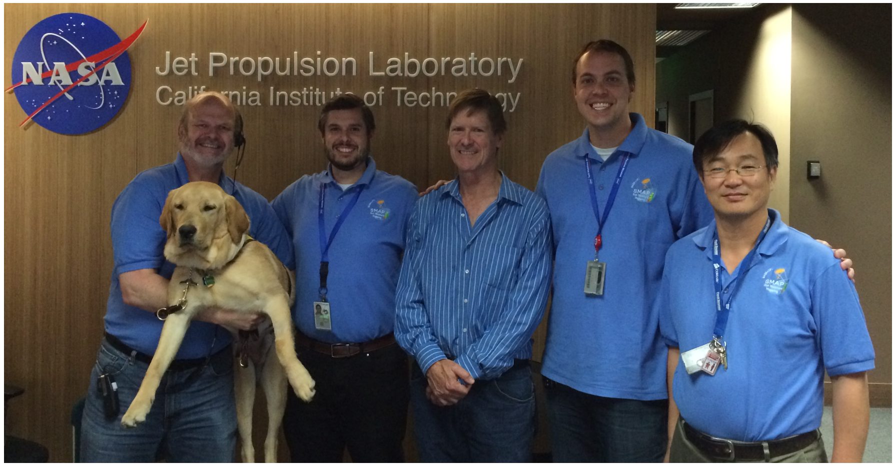


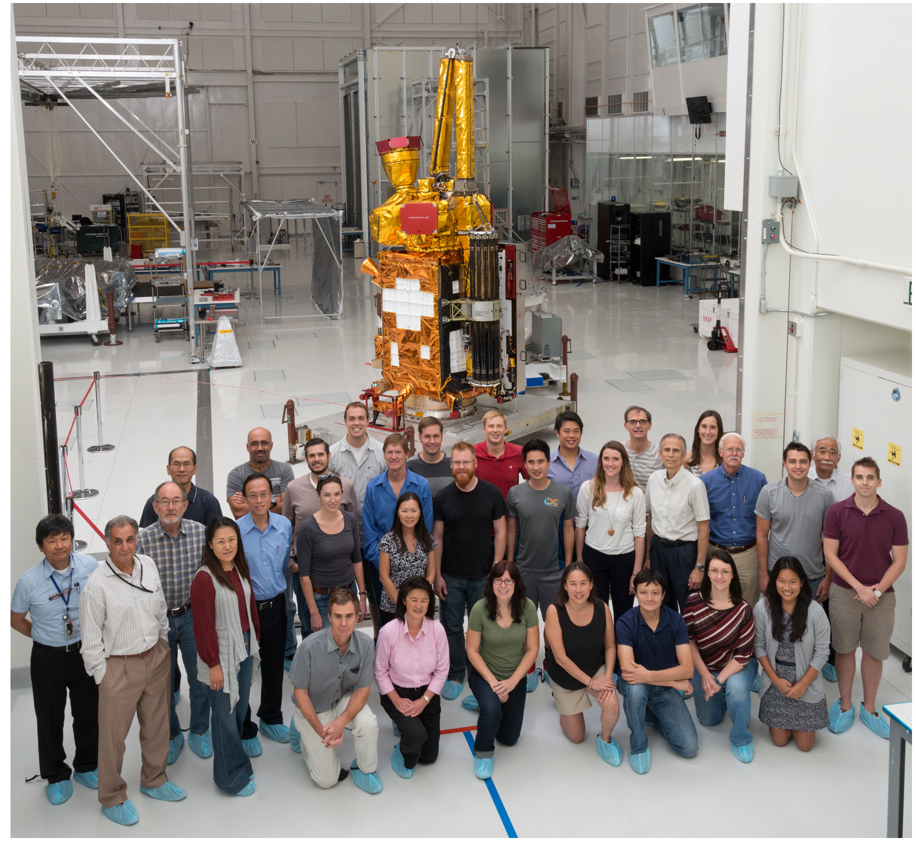
NASA's SMAP-Based Soil Moisture Measurements Jan 2-9, 2017

- From the pubic "Eyes on the Earth" NASA tool
- http://eyes.jpl.nasa.gov

- SMAP GNC Subsystem meets all pointing accuracy requirements with significant margin
- SMAP appears to be meeting all Flight System level nadir pointing requirements with significant margin as well
  - Not all sources of error can be seen in telemetry
- GNC hardware is currently healthy and functioning nominally
- SMAP is 2/3 of the way through its prime science mission and Radiometer continues to produce high accuracy soil moisture measurements daily (see images above)
- **The SMAP engineering challenge, to design a stable nadir platform with large spun antenna, has been an unqualified success**

Acknowledgements



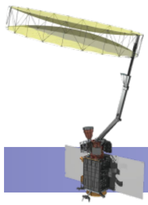


The Authors Would Like to Thank:

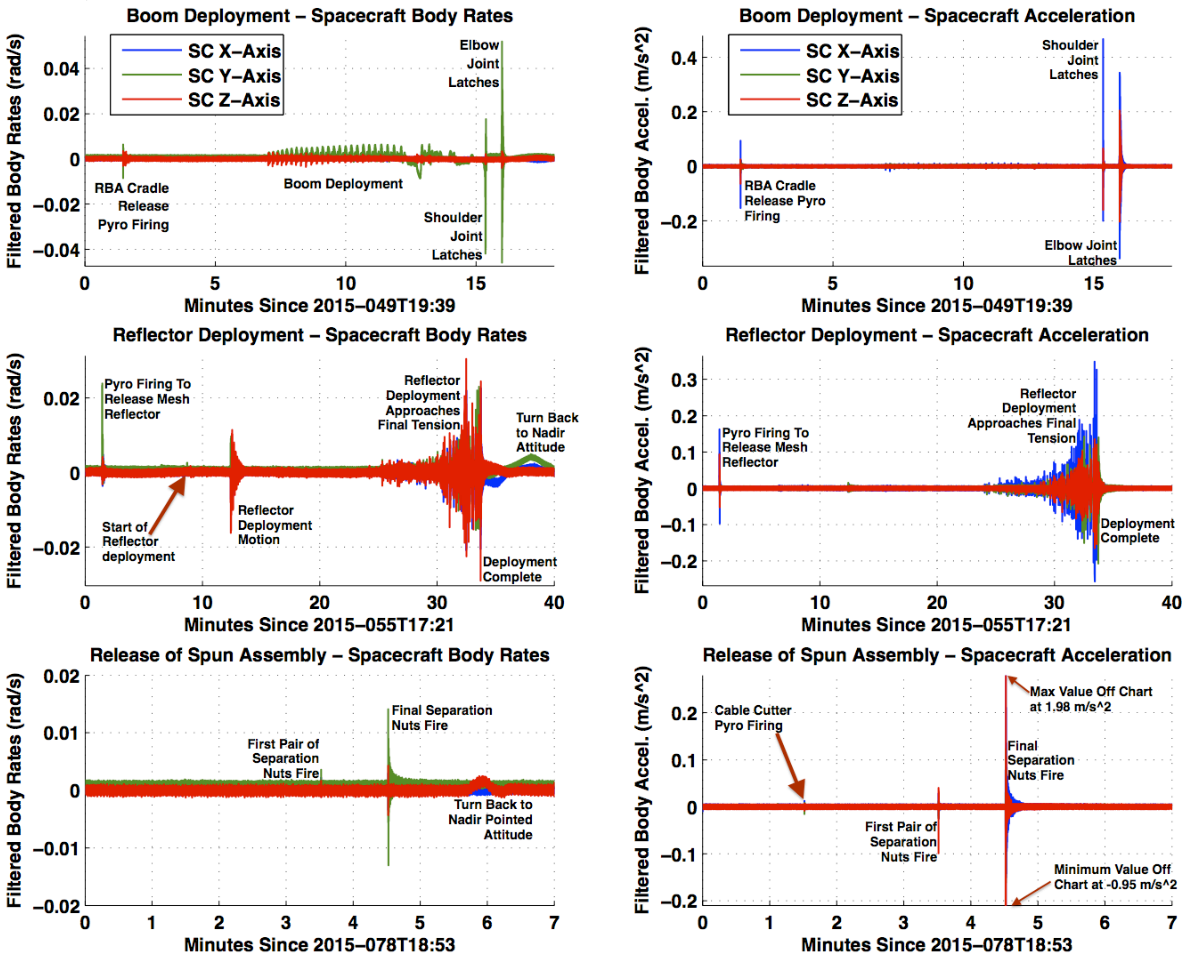
- The SMAP GNC Operations Team: Dan Eldred Shawn Johnson, Bryan Kang, and Matt Wette
- The SMAP GNC Control Analysis Team
- The SMAP GNC Hardware Team
- The SMAP Flight Operations Team

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

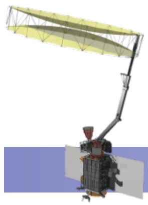
Backup Slides



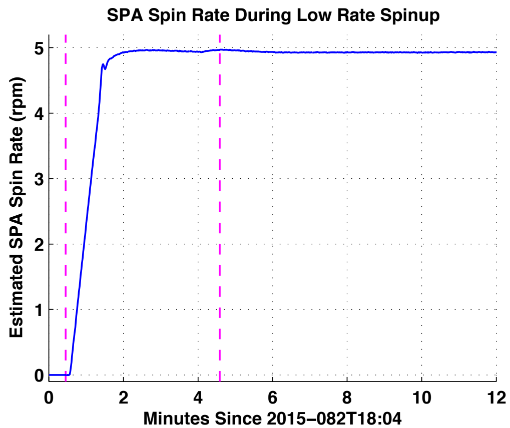
Deployment Events

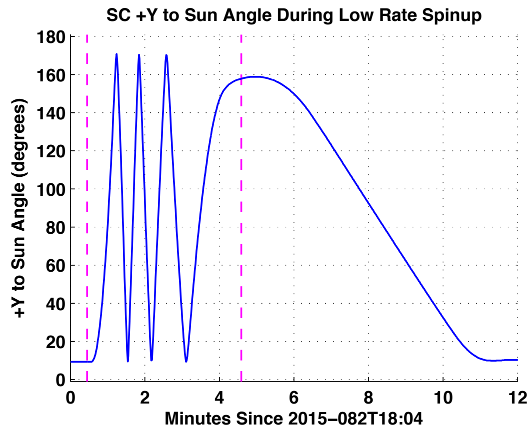


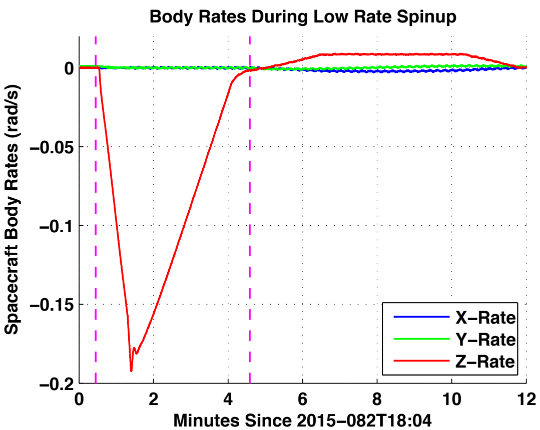
- Commissioning Included 3 Major Deployment Events
  - Boom Deployment
  - Reflector Deployment
  - Release of SPA (Pyro Firing event)
- GNC transitioned to IDLE mode for deployments (attitude control was inactive during activities)
- GNC continued attitude estimation and maintained constant RWA spin-rates
- High-Rate (> 100Hz) IRU telemetry used for 2ndary confirmation of deployment success
- Y-axis momentum bias of +8.25 Nms added for boom and reflector deployments
  - Added for gyroscopic stability to keep solar arrays near the sun
  - Attitude drift during boom deployment: [Y,Z] = [2.9, 14.9] (deg) in 16 minutes
  - Attitude drift during reflector deployment: [Y,Z] = [3.5, 15.8] (deg) in 33 minutes
- IRU easily detected every pyro firing of the mission



Low Rate Spin-Up Activity

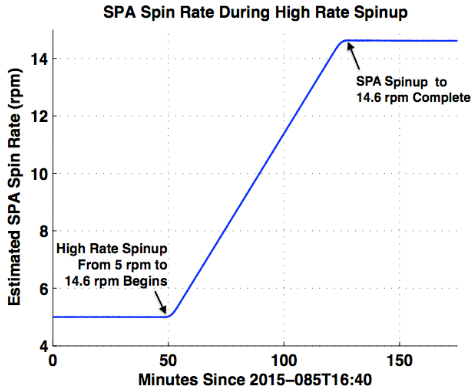


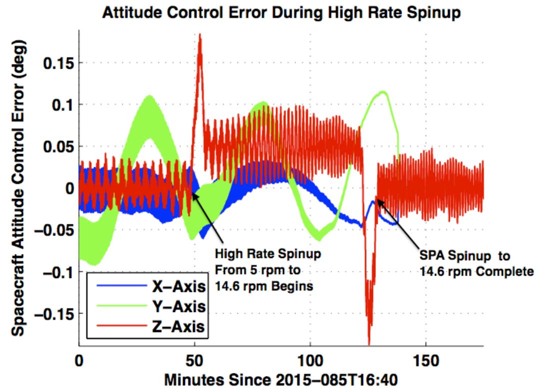


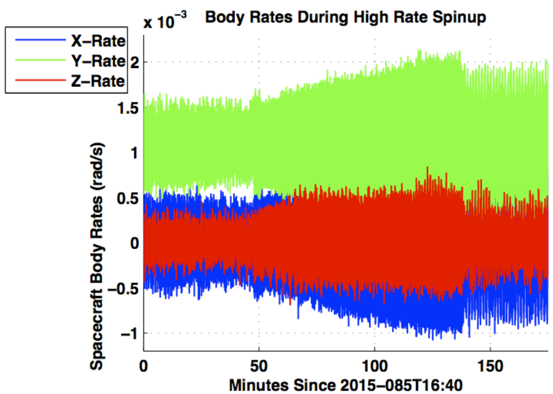


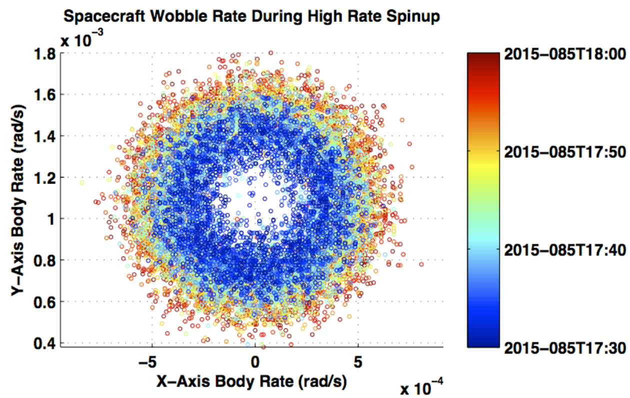
- During Low Rate Spin-Up SPA goes from 0 RPM to 5 RPM in ~80 seconds
- Torque from spin motor overwhelms RWA controller and the spacecraft tumbles (by design)
- Low Rate Spin-Up only performed once (i.e. the spacecraft has never spun down)
- During Spin-Up spacecraft tumbled at 11 deg/s around the Z-axis
  - Highest body rate of mission
- Spacecraft tumbled 3.5 full revolutions before RWA controller regained rate control
- After RWA control regained, 159 deg Z-axis turn to get solar arrays back to the Sun
  - Low Rate Spin-Up was first time Sun reached –Y facing Sun Sensor
- Spin-up telemetry used to calibrate spun inertia
  - Izz Spun: 234.7 kg-m^2
  - This was 4.0 kg-m^2 less than pre-launch estimate

High Rate Spin-Up Activity

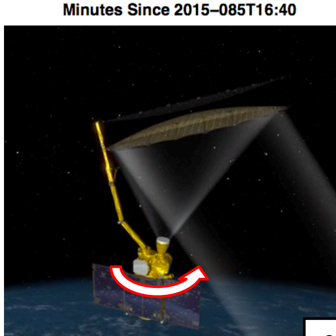


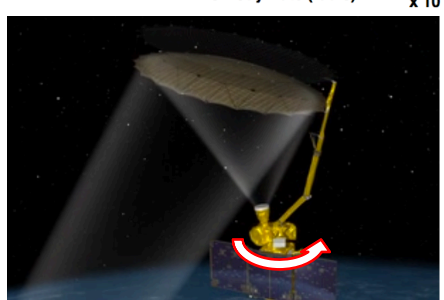






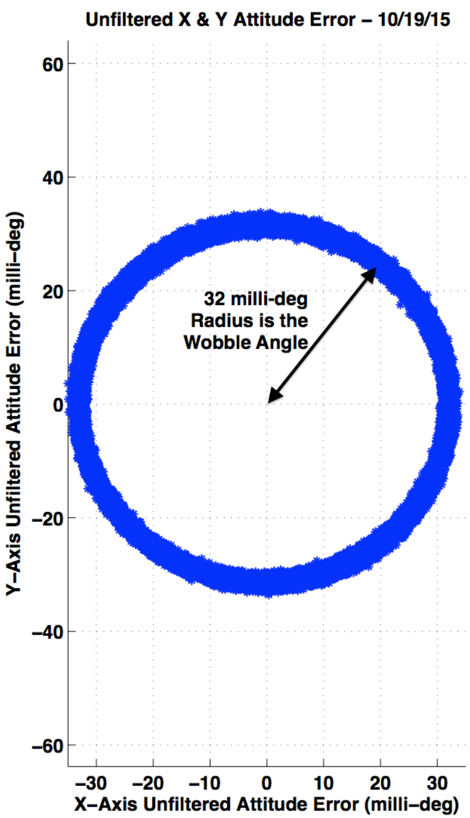
- During High Rate Spin-Up SPA goes from 5 RPM to 14.6 RPM in ~80 **minutes**
- RWA control and nadir pointing maintained through activity
- Controller uses looser gain set when SPA rate is: 0 ≤ (SPA Rate) ≤ 14.6 RPM
  - Notch filter used to mask wobble frequency
  - Notch frequency: 0.243 Hz
- **Attitude control performance while spinning:**
  - Does not include wobble angle, since this is intentionally uncontrolled
  - Attitude error: zero mean

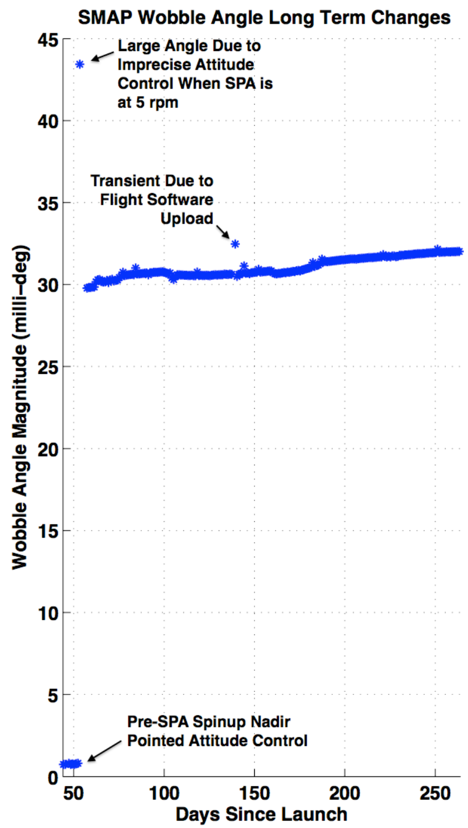




Stills from animation of science-rate spinning

Wobble Angle History





- Wobble present due to offset between SPA center of mass offset and spacecraft spin-axis
- Wobble rate grows as a function of SPA spin rate, wobble angle should be ~constant
- GNC operations team observed that wobble angle has continued to grow slowly over the course of the mission
- Current wobble angle: 34 milli-degree